Commissioning an Electron Gun

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ABSTRACT

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All electron guns must be commissioned before they can be used in a beam line. The commissioning of an electron gun refers to the process of placing the gun under vacuum and outgassing the cathode and high-voltage apparatus. Electron guns require a vacuum of at least 10^{-6} torr in order to function safely. Any worse and the electrons may interact with the residual gas and may backfire into the gun, causing damage to the electronics. The gun should first be baked, then cleaned, and then finally run; first without current, then without voltage, then with both, with the inhibiting grid at maximum. This procedure will ensure that the electron gun is properly commissioned and ready for use. This procedure was developed and used at Fermi National Accelerator Laboratory.

INTRODUCTION

An electron gun works by applying a current to the cathode; in order to heat the cathode and "boil" off electrons, the current is commonly between 1.2-3.0 amperes. The electrons are then accelerated by an electric field with a typical range of 0-60 kiloelectron volts (keV). By altering either the voltage or the current, the characteristics of the beam can be changed. A higher current means more electrons boiling off; a higher voltage means that the electrons will have a higher energy level. A magnetic field is used as a lens to focus the resulting electron beam. After the gun is powered up, an electric grid is used to either promote or inhibit the beam, negating the need to keep turning the device on or off. The grid also allows the beam to be pulsed by turning it on and off very quickly. Dual power supplies are used to run electron guns — one to control the gun; the other to provide high voltage. The purpose of this paper is to give an overview of the correct procedure for commissioning an electron gun and relaying an example of such commissioning. The gun used at Fermilab will ultimately be added to a particle beam line and be used to scan the beam. This works by measuring the deflection of the electrons by the charged beam and can reveal many characteristics of the particle beam such as transverse and longitudinal lengths and bunch size.

Proper vacuum is a necessity to the correct operation of an electron beam. A gun must be properly cleaned and optionally baked out before being installed into any vacuum system. Multiple pumps are used to take the vacuum level down to the required pressures. After this, an ion pump is used to remove the gas particles that result from the electron beam striking an object. As long as the vacuum is less than 10^{-6} torr, most of the electrons will move down the beam line and impact the target without difficulty. At vacuums greater than 10^{-6} torr, however, the odds increase that the electrons will be deflected by gas particles. If too many particles are deflected into the gun, damage may be done to the electronics within the gun. At the very least, the beam will be either faint or blocked.

Electron guns can be hazardous if used incorrectly, and so the utmost care and stringent safety precautions must be practiced to ensure operator safety. Proper radiation shielding is vital for the safety of the operators while an electron beam is being run. The accelerating electrons emit X-rays, which may have a high enough energy to damage human cells. Electron beams must be run in properly prepared beam enclosures with a safety interlock system in place to prevent accidental harm. Due to the high voltage, the gun must be correctly grounded in the beam line.

The electron beam is controlled by altering the current, voltage, Wehnelt (grid), magnetic lens, and X-Y deflection coils. The voltage determines the energy of the beam. The current determines how many electrons are in the beam. The grid can be used to pulse the beam. The magnetic lens consists of a wire coil that has a current run through it to produce a magnetic field approximately parallel to the beam. Electrons on the beam path are unaffected, while electrons off the beam path experience a force pushing them towards the correct path. The X-Y deflection coils consist of two pairs of electromagnetic coils positioned down-beam from the lens. By running current through the coils, a deflecting force is produced that is perpendicular to the beam in a direction depending on which coil is used. These coils can be used to aim, stretch, or compress the beam. The current at the anode can be measured to aid in the centering of the electron beam. A minimum anode current corresponds with a centered beam.

If the cathode temperature (current) is low and the energy (voltage) is high, then the electron emission has an exponential relationship with cathode temperature and is derived by the equation: $J = AT^2e^{-\Phi\kappa}$, where J is the density of the emission current in amps/cm^2, A is

Richardson's constant, which varies depending on the cathode but has units of amps/cm^2/degrees K^2, T is cathode temperature in degrees Kelvin, Φ is the work function of the cathode material in electron volts, and κ is Boltzmann's constant or 8.6×10^{-5} electron volts/degree Kelvin. If the cathode temperature is higher while the energy is lower, the relationship takes the form:
$J = 2.335 \times 10^{-6} V^{3/2} / d^2$, where V is high-energy potential on the cathode in volts and d is the distance between the cathode and anode in cm. By using these equations, it is possible to determine the correct amount of energy and current to apply in order to achieve a desired beam density. It is good to keep in mind, however, that the higher the cathode temperature the shorter the lifespan of the cathode.

MATERIALS AND METHODS

The procedure outlined below was used to commission a Kimball Electronics EGH-6210/EGPS-6210 Electron Gun System [1]. The gun was powered by an EGPS-6210B Power System and a Glassman High Voltage Power Supply. Procedures may vary depending on model and manufacturer.

The first step in commissioning an electron gun is to clean it. A clean room environment must be in place from the point where the gun is cleaned to when it is placed under vacuum. Standard precautions including the wearing of gloves and shoe covers as well as the sole use of deionized water must be taken. Great care must be taken while cleaning the gun that no damage occurs from rough handling. Any oil or chemical residue must be removed, as they will spoil the vacuum system. Isopropanol is an effective cleaning agent for the outside of the gun and compressed nitrogen can be used to blow out dust and dirt. If an extreme amount of cleanliness is required, the gun may be disassembled, cleaned with a specialized solution (such as Micro-90), and then placed into an ultrasound bath. Optionally, the gun may be baked out to ensure maximum cleanliness. A temperature of up to 200 °C is usually safe (be sure to check) as long as the cables are removed prior to the baking. A bake-out usually lasts several hours or days.

Once the gun is cleaned, it can be tested. It is almost always a better idea to commission an electron gun before adding it to its permanent home, as it allows for the use of a setup designed specifically to test the gun. A seal, typically a copper gasket, must be applied where the gun meets the beam line in order to ensure vacuum integrity. The gun must be bolted into place evenly by tightening the bolts gradually and evenly so that the seal ends up snug and centered instead of lopsided. Care should be taken so that no damage befalls the gun's insulators. Typical test beam lines are simple affairs, merely a pipe ending in a cross with a window installed on one of the six ports. A camera can then be mounted to observe the window and a target (possibly an aluminum or phosphorus screen) is set in the cross. Thus, when the gun is turned on, the beam impinges on the screen which releases photons. These photons are picked up by the camera and the spot can be seen. The spot can then be focused with the lens and moved with the X-Y deflection coils. First, however, the correct vacuum must be attained.

Once the gun is connected to the test beam line, the vacuum pumps may be run. Most commonly, two pumps are used, a rough pump and a turbo-molecular pump, in order to lower the vacuum to the level at which an ion pump may take over. The ion pump is usually accompanied by a meter for monitoring the residual gas pressure. If the vacuum is dropping slowly or not at all, there is probably a leak in the system. In that case, the whole system must be tested for leaks and repaired if possible.

Once the vacuum level is at least 10^{-6} torr or less, preferably around 10^{-7}, the gun is ready for the next step of its commissioning. First the gun must be run at high voltage. Typically, the gun is first stepped up to 10 keV; then the vacuum level is checked. When the vacuum stabilizes, the energy is then slowly and steadily ramped up, usually ending around 60 keV. There will most likely be discharging in the gun as the energy is turned up; this is normal. If the discharging does not cease, however, there is a problem with the gun and the power must be cut.

Next the cathode current is increased with the high voltage off. The current required depends on the cathode; for a lanthanum hexaboride cathode, the current used ranges from 1.6-3.8 amps. The cathode must be heated up slowly, as it will almost certainly outgas, lowering the quality of the vacuum. Patience is required for this step, for it may take hours or days for the cathode to completely outgas and the vacuum quality to restore itself; once it has, the next step of electron gun commissioning can be performed.

The next step is to run both the current and the high voltage with the Wehnelt bias (grid) set to full. This simulates the environment of running beam without the attendant hazards of radiation. The energy should be set to 10 keV and the cathode then heated with a current appropriate for whatever material it is made of. Then the energy is slowly increased, again usually to 60 keV. This step too may take quite a while, hours or even days. The vacuum must be closely monitored as the energy goes up to ensure no accidental damage to the gun is inadvertently caused. Once the vacuum stays solid, the last step in electron gun commissioning may commence.

The last step in electron gun commissioning is centering and focusing the beam. This is the first time that beam has actually been run in this procedure and as such is the first time radiation is produced. The area where the gun is being run should be carefully tested to ensure that radiation levels are within safety limits. The beam may be adjusted two ways: by careful manipulation of the lens and X-Y deflection coils, or by physically moving the gun’s parts. The second option should only be undertaken if the beam is so completely off that the first option is useless. Great care must be taken while adjusting the gun that no damage occurs. Typically, the beam is centered by firing it at a target. The target gives off light that is observed by a camera; usually the light is reflected to the camera so that no X-rays actually contact the camera and cause damage, and from the picture the camera provides, the spot can be adjusted and centered. Once the beam is centered, the gun's commissioning is complete and it can be placed into its final resting place and used for whatever purpose necessary.

RESULTS

When the electron gun was commissioned at Fermilab, several factors led to the process running behind schedule. Most had to do with waiting for parts to come in or people to come back from vacation and so are not relevant to this paper. What is relevant are the errors committed and the solutions used to resolve them. Note that this gun was attached to a beam line designed solely for the purpose of commissioning the gun. The line consisted of a straight pipe ending in a cross into which a phosphor screen was placed. A window was placed on one of the cross's apertures; the others were covered with blank flanges. A camera was mounted with a mirror and a lens to reflect and focus the light into the camera. An ion pump was placed on top of the gun.

Cleaning proceeded without incident. It took a day to lower the gun and beam line to the correct vacuum because the optional bake-out had not been undertaken. The gun and beam line were then transferred to a cave and preparations were made to run the gun. A difficulty arose when it became clear that the hardware on the computer was incompatible with the camera. The computer needed a FireWire in order to communicate with the camera. While one was being procured, we noticed that the phosphor screen had fallen out of its holder, rendering the entire setup useless. The gun and beam line were brought back to the clean room where a new screen and holder were fitted in. When vacuum failed to reassert itself, the gun was baked out for about a day. The gun and line were then moved back out to the cave.

Once the interlock system was set up again, commissioning recommenced. The high voltage was applied without incident, but the cathode heating took several days because the vacuum quality kept going sour. The next step of running both energy and current took even longer, requiring almost a week to complete. The amount of time taken was exacerbated by several power outages — one planned, the rest not — which shut down the ion pump and increased the time necessary to restore good vacuum.

During this time a FireWire card was procured and installed, but the software turned out to be incompatible. The correct, updated driver was not installed and proved very difficult to find. This did not significantly add to the delay, as another scientist's personal laptop was used instead. The camera had to be adjusted several times to get the image into focus. Even once the image was in focus, there was difficulty focusing the electron beam onto the target, as the magnetic field from the ion pump's magnet was revealed to be interfering with the beam. Once that was fixed, alignment proceeded.

DISCUSSION/CONCLUSION

Commissioning an electron gun is necessary to ensure optimal performance of the gun. If any step in the commissioning procedure is missed, then the gun may not perform to standard and may even become damaged. The commissioning process takes time but is vital to the successful operation of the gun. The main concern during commissioning is the integrity of the vacuum; nothing else matters as much. If the vacuum quality goes, the gun must either shut down or have its energy and current decreased. Increases in energy in current must be slow or the corresponding change in vacuum quality may be too quick to be caught by human operators.

Proper interlock techniques should be observed at all times and no one should be in the vicinity of the electron gun during operation. Care must be taken at all times that the gun is not subjected to bumps or shocks, as the delicate internal components of the gun can easily be destroyed or have their alignment thrown off. The same rule applies for any time the gun is to be cleaned or worked on, for example, adjusting the alignment. Electron guns are useful for many applications if commissioned properly, according to the correct procedure.

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[1] Kimball Physics Technical Staff, *EGH-6210A/EGPS-6210B Electron Gun and Power Supply System*, Wilton, NH: Kimball Physics, Inc., 2009.